Project ID: mat213

Active Monitoring of Composite Structures through Embedded Synthetic Fiber Sensor

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Relevance

Current and future automobiles will increasingly use composite materials in their structures to reduce weight and increase fuel/energy efficiency. These structures, especially the critical parts such as battery housing, must be monitored for safety. The vehicle's outer body structure, often exposed to extreme conditions and mechanical impacts, should also be closely monitored for its safety and to prevent failures. Innovative methods to monitor thermo-mechanical changes to these composite parts will help provide early warning of any imminent failures and enable precautionary measures to be taken to ensure safety.

Overview

Timeline Program duration: 2020/06 – 2021/03

TASKS	MONTHS AFTER PROJECT INITIATION									% Total Man Hours
	1	2	3	4	5	6	7	8	9	
1. Develop AMCOS System Architecture										8%
2. Investigate Fiber Response and Placement										17%
3. Develop Electronic Reader and Software										26%
4. Assemble the AMCOS Benchtop Prototype and Perform Preliminary Tests										17%
5. Demonstrate Feasibility of the AMCOS System										13%
6. Explore Commercial Potential and Product Viability										8%
7. Manage Program and Submit Reports										11%
Milestones				1			2		3	100%

Milestone 1: System design complete.
Milestone 2: Subsystems (sensors embedding + connectorization, reader) complete.
Milestone 3: Phase I prototype complete.

FY20/21 Total Project Budget: $200,000 (fully funded by DOE)
Partner agencies: DOE VTO

Barriers for widespread implementation of composite materials*:

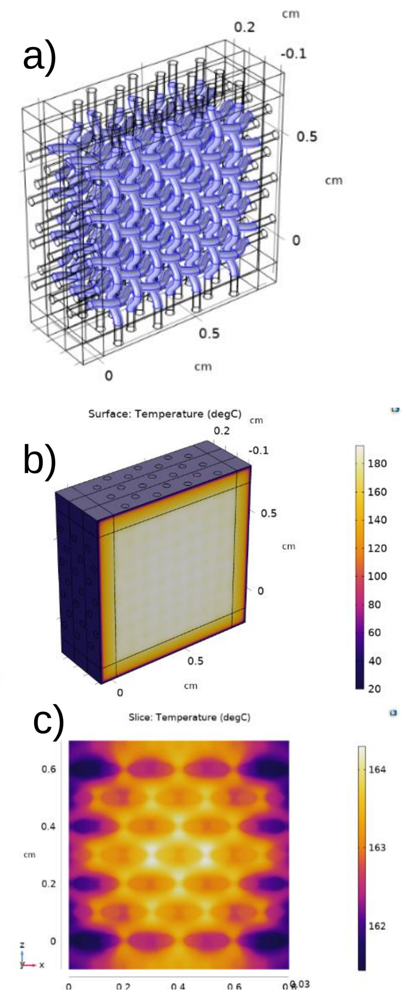
- Lack of understanding of properties with respect to fracture and energy absorption
- Lack of predictive engineering and modeling tools
- Lack of high-volume manufacturing capability

*Light-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials Workshop Report, February 2013

AMCOS System Architecture

- **Analyzed DOE requirements for AMCOS** and defined target applications and system properties, focusing on automotive components from composite materials.
- **Designed the AMCOS Phase I system,** taking into account the desired specifications.
- Performed initial tests to determine the need for fiber twisting, connector type, and optimal fiber length.
- **Built a heat-transfer model in COMSOL** to evaluate heat transfer capabilities of fibers embedded in composite materials.

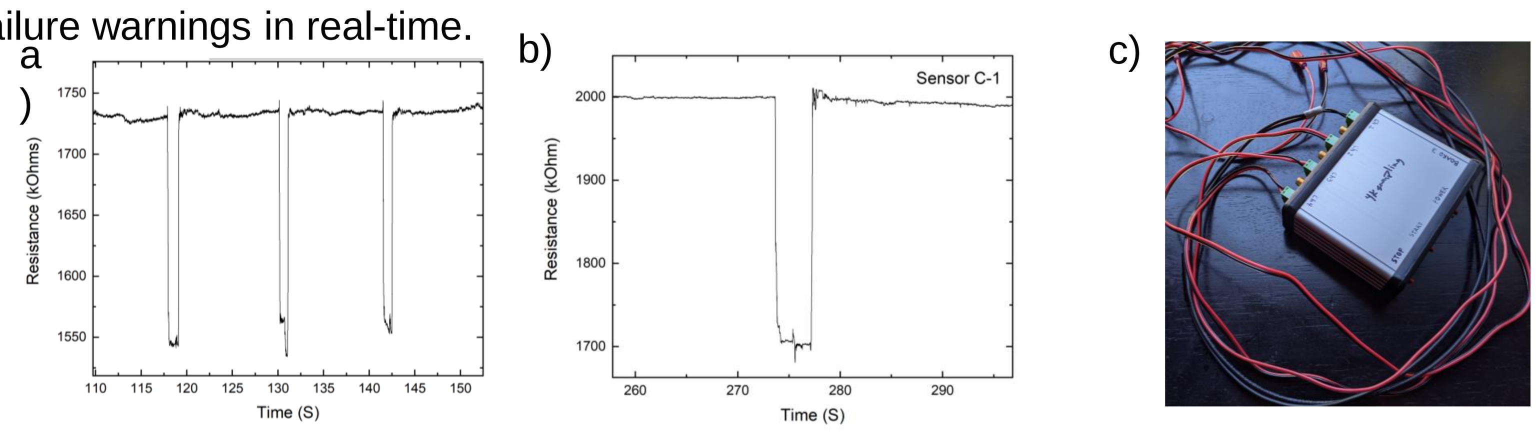
Electrically terminated sensor fibers embedded within composite test panel.



Heat transfer model.
a) Woven composite structure.
b) Heat source [100 W/cm^2] on one face of the material block.
c) Thermal heatmap of the improved nylon sample, showing a temperature of approx. 163°C around the center of the panel.

Electronic Reader and Software

The **data-acquisition speed** of the electronic reader was **increased from 1 kHz to 4 kHz** to better capture impact events, which happen on the ~ms timescale. This is sufficient to capture impact events in detail during operation in an automotive environment and generate structural failure warnings in real-time.



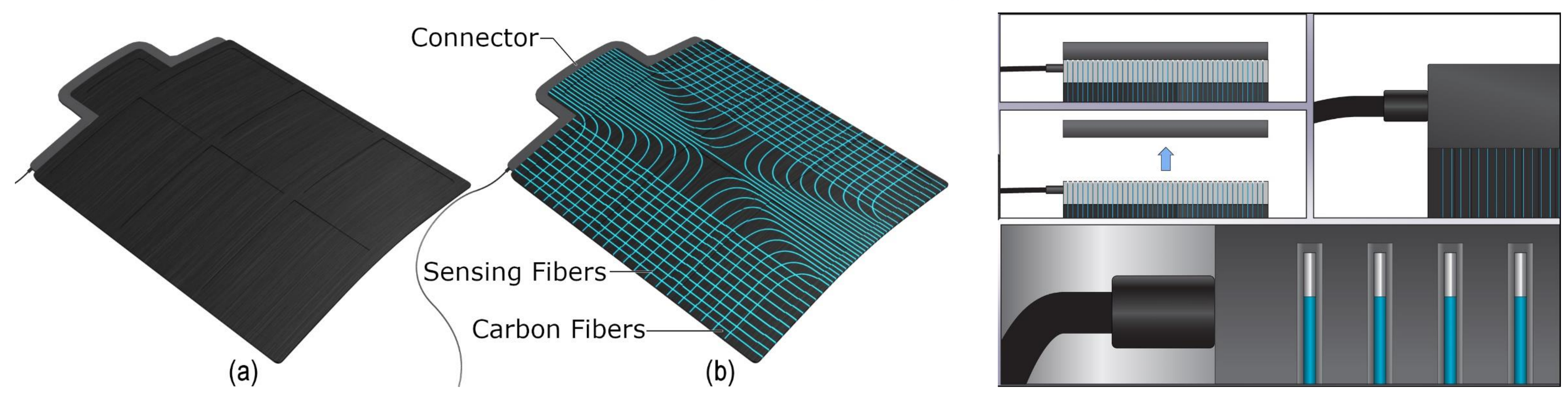
A comparison of impact points from two tests using (a) 500 Hz and (b) 4000 Hz sampling rates on the DAQ board. Both were impact tests in an Instron Dynatup machine with an impact energy of <10 J. The impact caused the resistance to spike downwards, and after a delay of several seconds, the resistance returned to its initial position. (c) Compact multi-channel electronic reader.

Collaboration

Test coupon fabrication and mechanical testing was performed in collaboration with

M.C. GILL COMPOSITES CENTER
USC VITERBI SCHOOL OF ENGINEERING

Future Work Plan



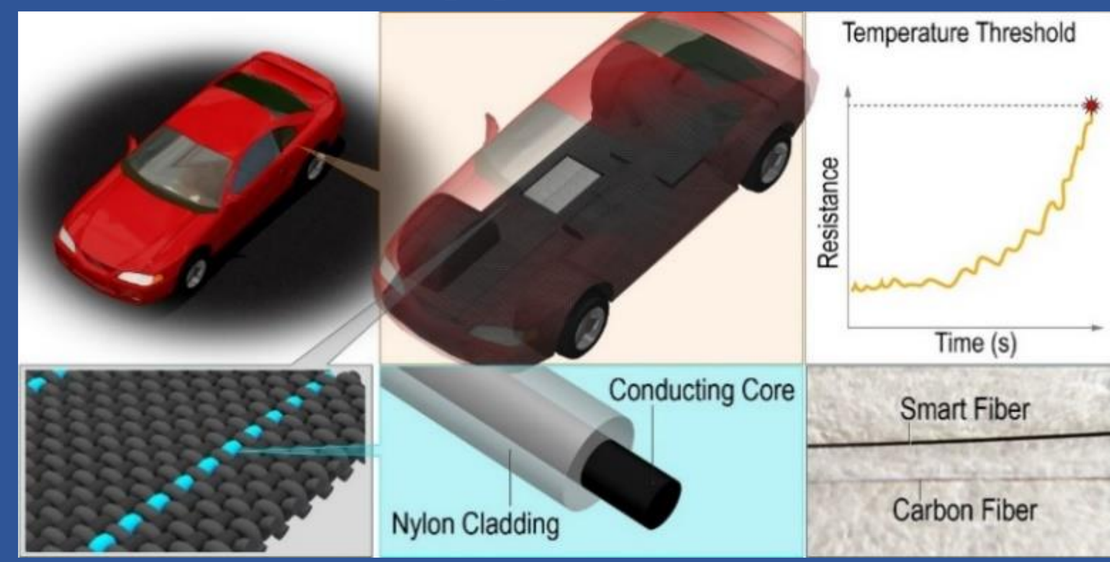
The technology will be matured further by optimizing the sensor spacing, testing smart fiber formulations to improve sensitivity, implementing mitigation strategies for charge buildup, and performing tests to mimic conditions during transport. A facsimile automotive part with embedded sensor fibers will be manufactured as the Phase II prototype. The Phase I algorithm will be improved by developing a machine learning-based approach to reliably distinguish between different defects and time-to-failure estimations. Phase II improvement will lead to a timely technology transition and commercialization.

Specific tasks to be completed:

- Improve System Architecture and Design Phase II Prototype
- Formulate and Improve Sensing Fibers
- Design and Build Electronic Reader and Multi-Channel Connector
- **Perform Mechanical and Environmental Tests in Laboratory Setting**
- Assemble Facsimile Automotive Part with Embedded Sensing Fibers
- Perform Vibration and Use Case Testing
- Develop and Test Machine Learning-Based Failure-Detection Algorithm
- Test the Phase II Prototype

Any proposed future work is subject to change based on funding levels.

Approach



Intellisense's AMCOS system monitors the structural health of automotive components. The innovation in AMCOS is its novel core-conductive sensing synthetic fibers that can be seamlessly integrated into composite parts to detect structural breakdown of the host material. An electronic reader digitizes the signal and an algorithm is used to warn the user if structural damage has occurred in the composite. The compact and lightweight design, as well as the fast readout, allow the use of AMCOS onboard automotive vehicles.

Fiber Response and Placement

A **comparison of fiber sensor formulations** for their **electrical and mechanical properties** was performed and a fiber type selected based on the findings that provide batch measurements of 241 kΩ for 10 bundles of 144 filaments at 1 ft length.

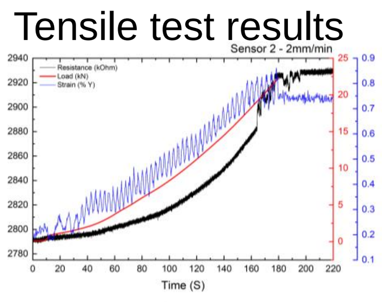
Single fiber bundles of lengths of up to 30 ft were tested for noise level. To maintain a noise error of <5%, the length of the double-twisted sensor line should be limited to approximately 12 ft, which is sufficient for automotive parts.

Benchtop Prototype and Preliminary Tests

Tensile test coupon fabrication

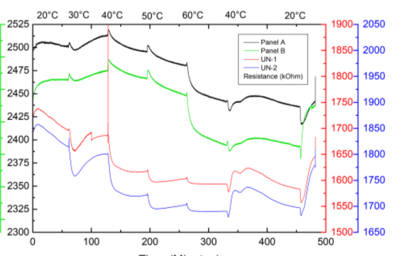
Tensile coupon made by leading the sensor out the sides rather than threading through the top, eliminating the need for cutting.

Tensile test results



A graphical representation of the resistance, load, and strain data versus time.

Thermal test results

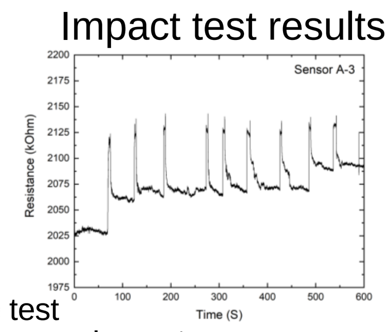


The thermal chamber was heated from 20°C to 60°C at 10°C intervals, and back down to 40°C and 20°C.

Impact test

Impact coupon loaded into the test frame, with a breather cloth to protect the sensors. A hole was cut in the center where the tup impacts the coupon.

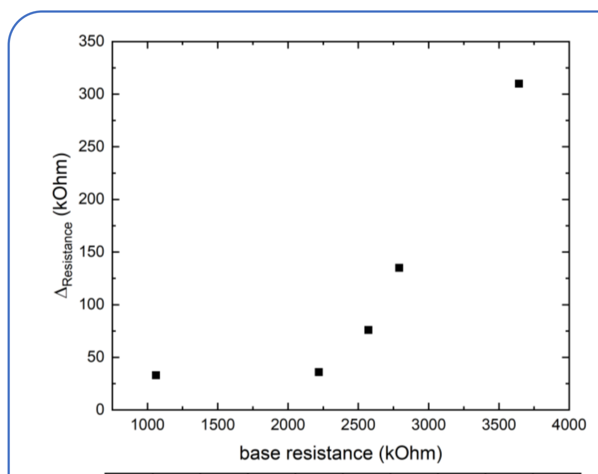
Impact test results



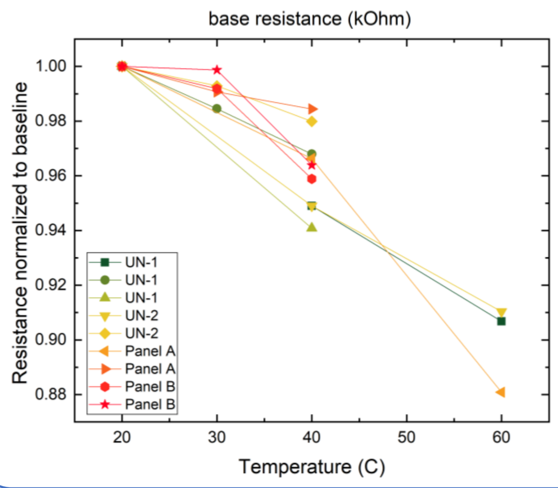
Impacts were performed in 3 groups of 3 with increasing impact energy.

- **Assembled test coupons** to test the response of fibers embedded in woven carbon fiber reenforced plastics to **tensile loading, impacts, and temperature changes.**
- **Improved manufacturing method,** from electrically terminating the sensors through the surface to an approach where the fiber's ingress and egress points are on the side of the composite to increase the reliability of the manufacturing method.
- Five tensile tests were performed, and the strain was compared to the resistance readings of the fibers. **The sensor fibers follow the strain readings within ~0.3% strain.** The change in resistance depends on the baseline resistance and needs to be calibrated accordingly.
- Performed impact tests on 3 test coupons with 4 sensor lines read in parallel at different distances from the impact location at increasing impact energies. The impact energies were below the damage threshold, and the sensors clearly show each impact up to ~3 in. distance from the impact site.
- Performed environmental tests: test coupons were placed in an environmental chamber and the temperature was increased and decreased stepwise with and without humidity control. To achieve repeatable readings, the sensor fibers were temperature cycled before testing.

Feasibility of the AMCOS System



The sensor fibers follow the strain readings within ~0.3% strain. The change in resistance is dependent on the baseline resistance and a **calibration curve** was established.



Linear relationship between temperature and resistance, when scaling the values by their baseline resistance. **Temperature changes of 1-2 °C can be detected reliably** when the fibers are calibrated individually

- The new manufacturing technique yielded **100% successful electrical termination**.
- From the temperature and tensile tests, a **calibration curve** based on the baseline resistance before the test was established that allows the correlation of strain and temperature to resistance measurements.
- An algorithm was developed to **automatically detect impact events** and determine peak properties.

Summary and Conclusion

In Phase I, synthetic polymer (nylon) smart fiber yarns were successfully embedded in woven composite panels, demonstrating the AMCOS technology's compatibility with composite manufacturing processes for automotive applications. Electrically conductive fiber sensor yarns were embedded in test coupons and electrically terminated for real-time continuous sensor readout. Their responses to external events, like strain, impact, and temperature changes, were experimentally measured.

The results showed that **the sensing fibers repeatably and accurately detect strain, impacts, and temperature changes, and that calibration procedures can be used to establish a quantitative relationship between resistance and strain as well as resistance and temperature**. An algorithm was developed to automatically identify impacts and distinguish them from other events, such as temperature changes.